Seeding Cool-Season Grasses to Suppress Broom Snakeweed (*Gutierrezia sarothrae*), Downy Brome (*Bromus tectorum*), and Weedy Forbs

Eric Thacker, Michael H. Ralphs, and Thomas A. Monaco*

Broom snakeweed (snakeweed) is an aggressive native range-weed found throughout arid and semiarid areas of the western United States, that increases following disturbances such as overgrazing, drought, or wildfire. Ecologically based strategies that include controlling snakeweed and reestablishing desirable herbaceous species are needed to restore productivity and diversity to invaded areas. The objective of this study was to compare the ability of selected introduced and native grass species and prostrate kochia (kochia) to prevent reinvasion of snakeweed, downy brome, and annual forbs following control. This field study was replicated at two sites (Howell and Nephi, Utah) within the sagebrush-steppe biome. Snakeweed and downy brome were controlled by picloram (0.25 kg/ha [0.22 lb/ac]) and glyphosate (1.5 kg/ha [1.3 lb/ac]). The seeding treatments were comprised of three introduced grasses and a mix of these species, three native grasses and a mix of these species, and kochia. The treatments were seeded into 3 by 15-m (10 by 50 ft) plots in October 2003. Frequency and biomass of seeded species, snakeweed, downy brome, other grasses, and annual forbs were measured in 2004, 2005, and 2008. Seeded species were evaluated for success of establishment and persistence, and their ability to restrict reinvasion of snakeweed, downy brome, and annual forbs. Crested wheatgrass and big squirreltail had the best initial establishment at both locations (> 75%). In contrast, kochia and Russian wildrye did not establish well at either site, and western wheatgrass did not establish well at Nephi. Snakeweed reestablishment was restricted in all treatments except the kochia treatments, in which kochia did not establish well. Frequency of downy brome increased at both sites, and annual forb frequency increased at Nephi to near 100%, but the better established grasses suppressed biomass production of these weedy species. Crested wheatgrass established best, had the greatest production, and provided greatest suppression of downy brome and annual weeds.

Nomenclature: Glyphosate; picloram; broom snakeweed, *Gutierrezia sarothrae* (Pursh) Britt. & Rusby GUESA; downy brome, *Bromus tectorum* L.; big squirreltail, *Elymus multisetus* (J.G. Sm.) Jones 'Sand Hollow'; crested wheatgrass, *Agropyron cristatum* (L.) Gaertner × *A. desertorum* (Fisch. Ex Link) Schultes 'Hycrest'; prostrate kochia, *Kochia prostrata* (L.) Schrader 'Immigrant'; Russian wildrye, *Psathyrostachys junceus* (Fisch.) Nevski 'Bozoisky'; western wheatgrass, *Pascopyrum smithii* (Rybd.) A. Löve 'Rosanna'.

Key words: Competition, weed resistant communities, successional weed management, poisonous plant.

Broom snakeweed (snakeweed) [*Guterrezia sarothrae* (Pursh) Britt. & Rusby] is an aggressive native subshrub found throughout semiarid rangelands of the western United States that increases following disturbances such as overgrazing, drought, or wildfire (Pieper and McDaniel 1989). It can dominate sites in the creosote bush, desert grassland, shortgrass prairie, salt-desert shrub, sagebrush-steppe, and pinyon/juniper plant communities. It is also toxic to livestock, causing abortions in cattle, sheep, and goats (Dollahite and Anthony 1957). Platt (1959) ranked it as one of the most undesirable plants on western rangelands.

Snakeweed can be controlled by herbicides (McDaniel and Duncan 1987; Whitson and Ferrell 1989) and prescribed burning (McDaniel et al. 1997). However, simply controlling it leaves a void, which will likely be filled by new snakeweed seedlings, downy brome (*Bromus tectorum* L.), or

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* Rangeland Technician and Rangeland Scientist, USDA/ARS Poisonous Plant Lab, Logan, UT 84341; Ecologist, USDA/ARS Forage and Range Lab, Logan, UT 84322. Current address of first author: Graduate Research Assistant, Wildland Resources Department, Utah State University, Logan, UT 84322. Corresponding author's E-mail: Michael.Ralphs@ars.usda.gov

Interpretive Summary

Broom snakeweed (snakeweed) is an aggressive native rangeweed that thrives after disturbances such as overgrazing, drought, or wildfire. Snakeweed can be controlled by herbicides and prescribed burning; however, managers must establish functional plant communities that will compete with snakeweed and restrict its reestablishment. The objective of this study was to compare the ability of selected introduced and native grass species and prostrate kochia (kochia) to establish and persist, and to restrict reinvasion of snakeweed, downy brome, and annual weeds in replicated field studies. Crested wheatgrass established well at both locations and had the greatest biomass production. Pubescent wheatgrass established well at Howell, and squirreltail established well at Nephi. These species that established well suppressed biomass of downy brome and annual grasses. Snakeweed reinvaded only the kochia treatments, in which kochia did not establish in the first year. Seeded cool season grasses will likely utilize the available soil moisture and nutrient resources and prevent reinvasion of snakeweed.

annual forbs. A competitive plant community must be established that will maximize the capture of soil moisture and nutrients (Call and Roundy 1991; Svejcar 2003) and thus restrict reestablishment of snakeweed, downy brome, and annual grasses. Previous research showed that interference between cool-season grasses and snakeweed seedlings in potted-plant trials, and between seeded rows in the field, increased mortality and restricted growth of snakeweed seedlings (Thacker et al. 2009).

This study was conducted within the framework of the successional weed management model (Sheley et al. 1996; Sheley and Krueger-Mangold 2003): 1) designed disturbances—herbicides were used to control snakeweed and associated vegetation to create site availability for desirable species; 2) controlled colonization—desirable species were seeded that are adapted to the site; and 3) controlled species performance—seeded species were intended to suppressed reestablishment and growth of snakeweed, downy brome, and annual forbs. The objectives of this field study were to compare the establishment of selected introduced and native cool season grasses and prostrate kochia (kochia) [*Kochia prostrata* (L.) Schrader 'Immigrant'] on two sites dominated by snakeweed, determine the persistence of these seedings after 5 yr, and evaluate the effects of these seeded species on reestablishment of snakeweed, downy brome, and annual forbs.

Methods and Materials

Site Description. Two sites were selected for this study. The Howell site was located 18 km (11 mi) west of Tremonton, Utah (41° 42.8297′ N, 112° 24.7745′ W). The site had a west-facing slope with an elevation of 1,420 m. The 46-yr average annual precipitation was 369 mm (14.5 in) (Figure 1), with 66% falling from

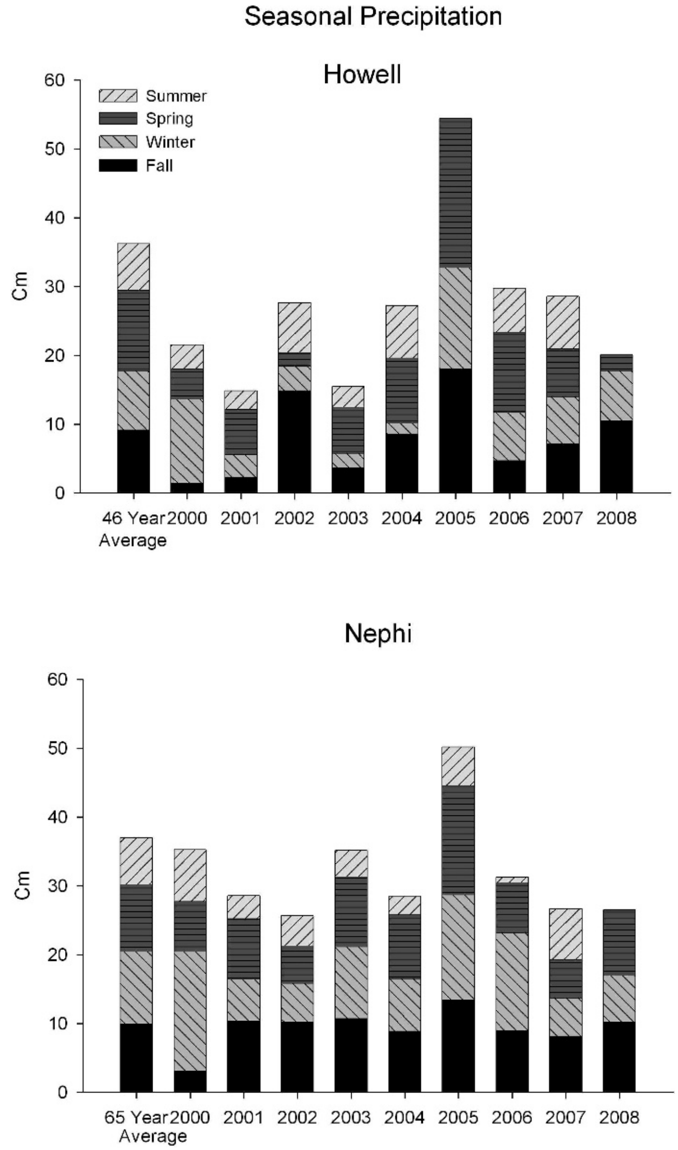

Figure 1. Seasonal water year precipitation at Howell and Nephi during the study and long-term average.

October through April. The soil was a loamy-skeletal, mixed, mesic, calcic haploxeroll (Hupp gravely silt loam). The ecological site was an upland Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) / bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) 'Goldar'] site, and had the potential to produce 1,540 kg/ha of total air-dried herbage (Chadwick 1975). The existing vegetation was dominated by Wyoming big sagebrush, snakeweed, downy brome, and redstem filaree (filaree) [*Erodium cicutarium* (L.) L'Her. ex Aiton]. The area had been grazed by cattle during the spring months for several decades. A wildfire burned the area in 1985, after which snakeweed increased and dominated the site.

The Nephi site was located 8 km west of Nephi, Utah (39° 42.2664′ N, 111° 54.9103′ W). The site occurred on

Table 1. Seeded species and treatments in this study.

Treatment symbol	Common name	Variety	Description
Introduced species			
CW	Crested wheatgrass	Hycrest	Early maturing, drought-resistant bunchgrass
PW	Pubescent wheatgrass	Luna	Easily-established, rhizomatous
RW	Russian wildrye	Bozoisky	Late maturing, bunchgrass
I. mix	Introduced grass mix		Equal portions of Crested, Pubescent and Russian
Koc	Kochia	Immigrant	Drought resistant shrub
Native species			
BB	Bluebunch wheatgrass	Goldar	Early maturing bunchgrass
WW	Western wheatgrass	Rosanna	Rhizomatous
ST	Squirreltail	Sand hollow	Short-lived bunchgrass
N. mix	Native grass mix		Equal portions of Bluebunch, Western and Squirreltail
Control treatments			
C	Untreated control		
SC	Snakeweed control		

an east-facing slope of an alluvial fan. The elevation was 1,542 m and the annual precipitation was 361 mm (Figure 1), with 59% arriving between October and April. The soil was a fine loamy, mixed xerolliccalciorthid (Firmage gravely loam, dry). The ecological site was an upland Wyoming big sagebrush / Indian ricegrass [*Achnatherum hymenoides* (Roem. & Schult) Barkworth] site, and had the potential to produce 808 kg/ha of air-dried herbage (Trickler 1984). The area was burned in 1996, which removed most of the sagebrush, and was subsequently invaded by snakeweed. Downy brome and Sandberg bluegrass (*Poa secunda* J. Presl.) were the dominant grasses, but there were remnants of Indian ricegrass, and needle-and-thread grass [*Hesperostipa comata* (Trin. & Rupr.) Barkworth]. There were a few forbs present on the site including sego lily (*Calochortus nuttallii* Torr. & A. Gray), scarlet globe mallow [*Sphaeralcea coccinea* (Nutt.) Rydb.], and filaree.

Seeding Experimental Design. The study was laid out in a randomized complete block design with four blocks. Each block had 11 plots (3 m by 15 m): nine seeding treatments, and two control plots (a nonseeded snakeweed control plot and an untreated control plot). The species and seeding treatments are described in Table 1. The grass seeding treatments were categorized as introduced or native species.

Treatment plots were sprayed in May 2001 with a tank mix of picloram (0.25 kg ae/ha) to control snakeweed and other broadleaf forbs (McDaniel and Duncan 1987; Whitson and Ferrell 1989), and glyphosate (1.5 kg ae/ha) to control downy brome and other grasses. Snakeweed control plots were sprayed with only picloram (0.25 kg/ha) to kill snakeweed and forbs without harming the grasses. The untreated control plots were not sprayed.

Grass seed was obtained from a commercial dealer[1] and the USDA/ARS Forage and Range Lab[2], and was certified for quality and germination (> 90% pure live seed). Grasses were seeded in October 2001 with a five-row flex planter[3] equipped with 2.5-cm depth bands to ensure consistent seeding depth. Row spacing was 30 cm. Seeding rate for the grasses was 6 to 8 kg/ha of pure live seed. The low precipitation on these sites would not support a stand seeded at higher rates (H. Horton, personal communication). The seeding failed to establish the first year due to drought (Figure 1). Treatment plots in both locations were sprayed again in April 2002 with glyphosate (1.5 kg/ha) in an attempt to control emerging downy brome, and again in October 2002 with imazapic (0.2 kg ae/ha) to control downy brome and other annual weeds prior to reseeding. A second seeding was attempted in fall 2002, but also failed. The few weeds that did emerge in the treatment plots were removed with a shovel in fall 2003. A third seeding was repeated in October 2003 using the initial rates and was successful. Kochia was seeded in March 2004 following snowmelt by dribbling seed on the soil surface at a rate of 5 kg/ha with the same five-row flex planter, but it did not establish. It was reseeded with a dribbler cart[4] in December 2004 before permanent snow cover and emerged in spring 2005. Seeding recommendations and rates are available for the Intermountain Region (Jensen et al. 2001) and Great Basin (Sheley et al. 2008).

Measurements. Establishment of seeded species was measured in June 2004 and 2005, and persistence was measured in June 2008. A frequency grid was used (Vogel and Masters 2001) consisting of twenty-five, 15 × 15-cm squares (five rows of 5 squares; 0.75 × 0.75-m frame). The 5 by 5-grid frame covered three drill rows when placed on the ground (15 squares), with two empty grid rows covering the interspaces between rows (10 squares). The number of squares containing one or more seeded plants was counted. The number of squares containing seeded plants was divided by the maximum potential (15 squares) to obtain percentage frequency of seeded species that established. Frequency of associated species (downy brome, other grasses and forbs) was counted in all 25 squares and their percentages were calculated to estimate change in composition of the total plant community. The frame was systematically placed at four locations within each plot at 3-m intervals, alternating on left and right sides to uniformly cover the plot.

Aboveground biomass production was estimated in June 2005 and 2008 by clipping all of the vegetation in a 0.25 by 1.0-m frame to a 3-cm stubble height. Two frames were clipped in each treatment plot. The frames were randomly placed over representative drill rows. Biomass was separated into categories of seeded species, downy brome, other grasses, and forbs. The plant material was dried in a forced air oven at 40 C for 48 hr and weighed.

The seeding treatments were evaluated to determine their ability to suppress reestablishment of snakeweed, downy brome, and annual forbs. The number of snakeweed plants in each plot was counted at the beginning of the study before site preparation, and annually following grass establishment. The change in frequency of downy brome and annual forbs (as measured in the frequency grid) and their clipped biomass represent their response to seeded species treatments.

A mixed model repeated measures ANOVA was used to analyze the following data: percent frequency of seeded species, percent frequency of downy brome and annual forbs, biomass production, and snakeweed density. Seeding plots were the experimental units and the four blocks were replications. Seeding treatments and locations were the fixed-effect factors, year was the repeated measure, and block was the random-effect factor. There were location by treatment and treatment by year interactions for most parameters ($P < 0.05$). Therefore, the models were reduced and analyzed separately for locations and years by one-way ANOVA to compare frequency of seeded species treatments in 2004 (establishment) and at the end of the study in 2008 (persistence), and reinvasion of downy brome, annual forbs, and density of snakeweed. Year effects of seeded species frequency were analyzed separately for each treatment and location by one-way ANOVA. Biomass production was analyzed for each vegetation class within each location, comparing treatments and years to determine change over time (2005 vs. 2008). Mean separations ($P = 0.05$) were used to determine differences between treatments using PD800 Macro in SAS (Saxton 1998). The percentage frequency data sets were transformed with an ARCSIN transformation. The study was repeated in space by using two independent sites, so inferences may be made to similar sagebrush-steppe ecosystems.

Results

Establishment of Seeded Species 2004. Percent establishment is defined here as the frequency of seeded species established in rows in 2004. Frequency of establishment differed among treatments at Howell ($P = 0.0001$). The introduced grass mix had the highest mean frequency of establishment (85%), followed closely by crested wheatgrass [*Agropyron cristatum* (L.) Gaertner × *A. desertorum* (Fisch. Ex Link) Schultes 'Hycrest'] (83%), pubescent wheatgrass [*Elytrigia intermedia* ssp. *trichophorum* (Host) Beauv., 'Luna'] (78%), then the native species big squirreltail (squirreltail) [*Elymus multisetus* (J.G. Sm.) Jones 'Sand Hollow'] (76%) and the native grass mix (74%) (Figure 2). Kochia did not establish the first year, but a few plants established in 2005. Of the grasses, western wheatgrass [*Pascopyrum smithii* (Rybd.) A. Löve 'Rosanna'] (40%) and Russian wildrye [*Psathyrostachys junceus* (Fisch.) Nevski 'Bozoisky'] (53%) had the lowest establishment the first year. Frequency of the rhizomatous grasses, pubescent and western wheatgrass, increased in 2005 (Figure 2).

Frequency of establishment also differed among treatments at Nephi ($P < 0.0001$). Squirreltail had the highest frequency of establishment (97%), followed by crested wheatgrass (89%) and the introduced grass mix (78%) (Figure 2). Similar to Howell, kochia had the lowest establishment (14%), along with the grasses Russian wildrye (28%) and western wheatgrass (35%). As at Howell, pubescent wheatgrass increased in 2005. All of the seeded species at Nephi experienced heavy rabbit herbivory during the first summer of establishment (2004). A rabbit-proof fence was constructed in late summer 2004 to prevent further depredation. However, suppression of the seeded grasses the first year may have affected their vigor, competitive ability, and production in 2005.

Persistence of Seeded Species 2008. Whereas the mean frequency of establishment averaged over all seeded species was similar at both locations in 2004 (61% Howell, 57% Nephi), the persistence of the seeded species treatments differed in 2008. In 2008, mean frequency of seeded species increased at Howell (82%), but declined at Nephi (42%). At Howell, the rhizomatous species western wheatgrass and pubescent wheatgrass had the greatest increase in frequency over the 5 years of the study (Figure 2). At Nephi, frequency of all the seeded species declined except western wheatgrass, the native mix, and kochia, which remained low.

Biomass Production. Biomass production at Howell was four times greater than at Nephi in 2005 ($P = 0.0001$) (Table 2). The Howell production potential was greater than at Nephi (1,540 kg/ha vs. 808 kg/ha, respectively, taken from the soil surveys [Chadwick 1975; Trickler 1984]), but the combination of above average spring precipitation (Figure 1) and the buildup of nutrients

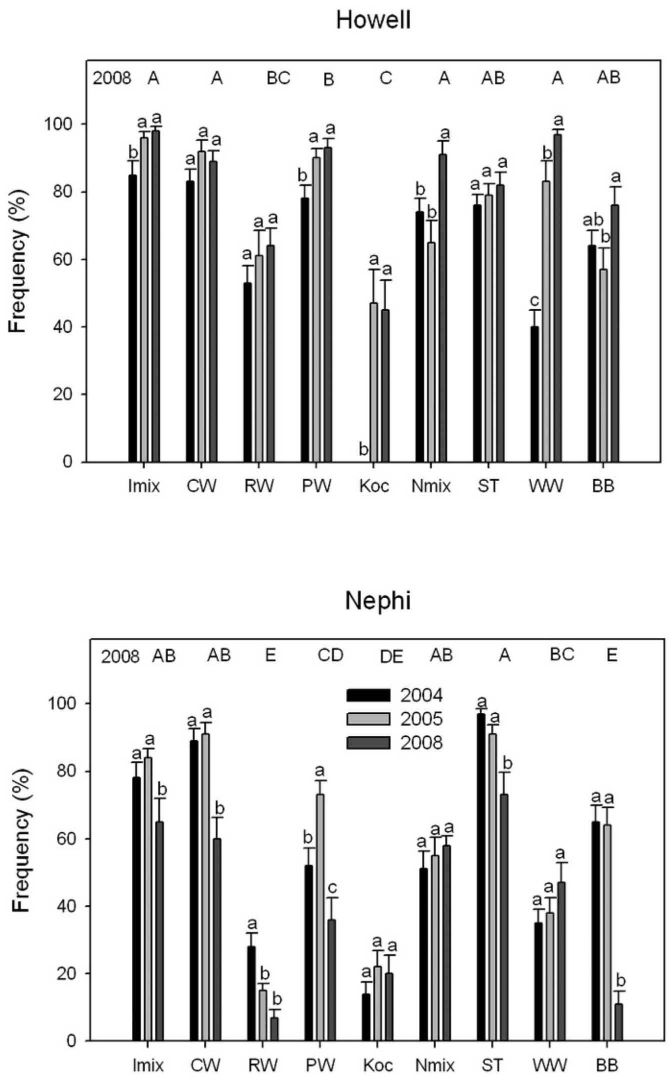

Figure 2. Frequency of seeded species over 5 years of the study at Howell and Nephi. Capital letters (ABCD) denote differences between seeded species treatments at the end of the study in 2008 ($P < 0.05$). Small letters (abc) denote differences between years within each treatment ($P < 0.05$).

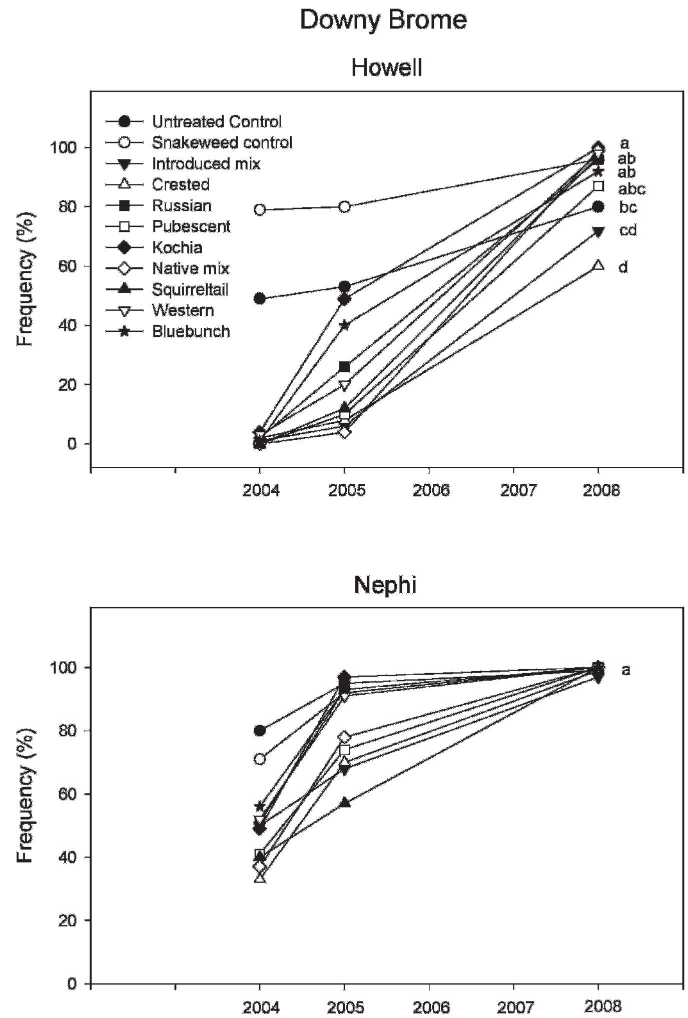

Figure 3. Frequency of downy brome in treatment plots at Howell and Nephi. Means in 2008 at the end of the study followed by different letters differ ($P < 0.05$).

during 3 yr of control efforts, sustained the exceptional biomass production at Howell. Although precipitation was also above average at Nephi (Figure 1), the abundance of downy brome and defoliation of the seeded grasses by rabbits the previous year may have restricted biomass production of the seeded species in 2005.

The Howell site had differences in seeded species biomass in 2005 ($P = 0.01$) (Table 2). The greatest biomass was in the introduced species mix (7,189 ± 606 kg/ha), pubescent wheatgrass (5,438 ± 504 kg/ha), and crested wheatgrass (5,131 ± 351 kg/ha). Western wheatgrass (2,819 ± 295 kg/ha) and bluebunch wheatgrass (2,988 ± 664 kg/ha) had the lowest biomass production. Biomass of seeded species at Howell declined in 2008; annual precipitation was only 57% of average, and growing season precipitation was only 2.3 cm. The introduced grass mix and crested wheatgrass had the greatest production in 2008 (Table 2).

The Nephi site also had significant differences in seeded species biomass ($P < 0.0001$). In 2005, squirreltail had significantly higher biomass production (909 ± 110.3 kg/ha) than all of the other seeded species (Table 2). At Nephi, the year difference was opposite the change at Howell. In 2008, biomass of crested wheatgrass (1,067 ± 109 kg/ha), the introduced grass mix (1,399 ± 229 kg/ha), and the native grass mix (879 ± 77 kg/ha) was more than double that in 2005. These grasses may have been suppressed by defoliation by rabbits in 2004 and the dominance of downy brome in 2005, but they apparently attained a competitive advantage by 2008.

Downy Brome. At Howell, downy brome was suppressed in all seeded plots in 2004 (Figure 3). In the snakeweed

Table 2. Biomass production (kg/ha dry weight) of seeded species, downy brome, and associated forage classes.

Seeding treatment	2005 Seed sp.	2005 Other grass	2005 Downy brome	2005 Forb	2008 Target	2008 Other grass	2008 Downy brome	2008 Forb
	kg/ha							
Howell								
I. mix[a]	7,189 a	0	0 c	0 b	3,251 a	0	9 d	-[b]
Crested	5,131 abc	0	0 c	0 b	2,223 b	0	38 cd	-
Russian	4,587 bcd	0	0 c	19 b	1,221 d	0	75 bcd	-
Pubescent	5,438 ab	509	0 c	0 b	2,013 bc	0	78 bcd	-
Kochia	-[d]	-	-	-	162 e	57	270 a	-
N. mix	3,201 cd	50	63 c	511 a	1,327 cd	0	84 bcd	-
Squirrel	4,567 bcd	0	97 c	192 ab	1,006 d	0	90 bcd	-
Western	2,819 d	27	219 bc	270 ab	1,173 d	0	62 bcd	-
Bluebunch	2,988 cd	0	71 c	289 ab	1,323 cd	0	122 b	-
Control	-	1,104[c]	607 ab	19 b	-	512	63 bcd	-
SC	-	848[c]	772 a	22 b	-	885	100 bc	-
Nephi								
I. mix	423 bc	0	267 cd	71 b	1,399 a	-	84 cd	0 c
Crested	523 b	0	342 abc	163 ab	1,067 ab	-	42 d	5 bc
Russian	63 d	0	411 abc	136 ab	77 d	-	200 ab	33 bc
Pubescent	457 bc	0	281 bcd	84 b	671 bc	-	112 cd	3 c
Kochia	-[d]	-	-	-	337 cd	-	128 bc	94 ab
N. mix	269 cd	0	360 abc	103 b	879 b	-	97 cd	0 c
Squirrel	909 a	0	161 d	51 b	821 b	-	77 cd	0 c
Western	168 d	0	433 abc	107 b	350 cd	-	145 bc	5 c
Bluebunch	434 bc	0	464 ab	82 b	115 d	-	252 *a*	23 bc
Control	-	87[c]	481 a	205 ab	-	-	142 bc	140 a
SC	-	591[c]	295 bc	289 a	-	-	148 bc	150 a

[a] Abbreviations (see Table 1); I. mix, Introduced species mix; N. mix, Native species mix; Control, Untreated control; SC, Snakeweed control; Crested, Crested wheatgrass; Russian, Russian wildrye; Pubescent, Pubescent wheatgrass; Squirrel, Squirreltail; Western, Western wheatgrass; Bluebunch, Bluebunch wheatgrass.

[b] Filaree dominated the annual forb category at Howell; its small, prostrate rosette made it difficult to clip.

[c] Sandberg bluegrass was the dominant "other grass" species.

[d] Kochia did not establish well; thus, biomass production was not clipped in its plots in 2005.

* Means within locations and columns followed by different letters differ ($P < 0.05$).

control plots, picloram killed the snakeweed and forbs, allowing the existing downy brome to increase. Downy brome increased in the seeded plots in 2005, but its frequency was inversely proportional to establishment of seeded species (Table 4); the species with the lowest establishment had the highest frequency of downy brome (kochia, bluebunch wheatgrass, and Russian wildrye). By 2008, downy brome increased in all of the plots, but crested wheatgrass showed some suppression of downy brome compared to the control (Figure 3; Table 5).

Downy brome was more abundant in the seeded species treatments at Nephi than at Howell in 2004 (Figure 3). Again, there was an inverse relationship with grass establishment (Table 4); crested and pubescent wheatgrass, and squirreltail and the native mix (dominated by squirreltail) had the best establishment and lowest frequency of downy brome. Although downy brome increased in 2005, squirreltail suppressed it better than other treatments. Downy brome increased to 100% frequency in all plots in 2008.

Although frequency of downy brome approached 100% in most of the treatment plots, seeded species that established well and persisted over the study suppressed downy brome biomass production in both 2005 and 2008 (Table 2). Crested wheatgrass and the introduced mix at Howell, and these two treatments in addition to squirreltail and the native mix at Nephi, had the best establishment, highest grass biomass production, and corresponding lowest downy brome biomass production in both locations.

Annual Forbs. Dominant weedy annual forbs at Howell were filaree and prickly lettuce (*Lactuca serriola* L.), and at Nephi, tumble mustard (*Sisymbrium altissimum* L.), filaree, clasping pepperweed (*Lepidium perfoliatum* L.), prickly lettuce, and bur buttercup [*Ranunculus testiculatus* Crantz; =*Ceratocephala testiculata* (Crantz) Roth]. In 2004 at Howell, frequency of annual forbs averaged 31% in the untreated and snakeweed control plots, compared to an average of 10% in the treated plots (Figure 4). The high rate of establishment of seeded grasses in most treatments accounted for the suppression of annual forbs. In 2005, forb frequency increased in the kochia and bluebunch wheatgrass treatments, which had the lowest establishment. Pubescent wheatgrass, crested wheatgrass, and the introduced mix continued to suppress forbs in 2008.

At Nephi, there was a flush of annual forbs in the seeded plots in 2004 the first year after seeding (Figure 4). The disturbance from site preparation and slow establishment of seeded species may have allowed the annual forbs and downy brome to establish. The overall decline in forb frequency in 2005 may have been due to the almost total dominance by downy brome. However, the grasses that established best (squirreltail and crested wheatgrass) had the lowest forb frequency. In 2008, crested wheatgrass and the introduced grass mix treatments showed a slight suppression of annual forbs (Figure 4). Filaree was the dominant annual forb in 2008. Although it was universally present, filaree plants were small and there was little biomass production (data not shown).

Native Species. Sandberg bluegrass was abundant in the untreated and snakeweed control plots at both Howell (32% frequency) and Nephi (43% frequency) in 2004 (data not shown). It comprised the majority of the other grass category of biomass production (Table 2). The glyphosate herbicide essentially killed Sandberg bluegrass in all the treatment plots. There were few native forbs at Howell. At Nephi, scarlet globe mallow (26% frequency) was the dominant native forb, and browse milkvetch (*Astragalus cibarius* Sheldon) was present (4% frequency) in the control and snakeweed control plots in 2004.

Snakeweed Reinvasion. Snakeweed density averaged five plants/m^2 at the beginning of the study prior to site preparation in 2001. The study was conducted during a region-wide drought (Figure 1) and most remaining snakeweed plants died between 2001and 2004 (Table 3). Spring precipitation in 2005 was 65% above average, and there was some snakeweed germination in this study and in adjacent studies. The kochia plots had the greatest establishment of new snakeweed seedlings at both locations (Table 3). During site preparation in 2001 through 2003, all vegetation on seeded plots was killed with herbicides. Kochia failed to establish in 2004, leaving the plots bare. Apparently, conditions were right during the wet spring of 2005 for snakeweed to germinate and establish in these kochia plots.

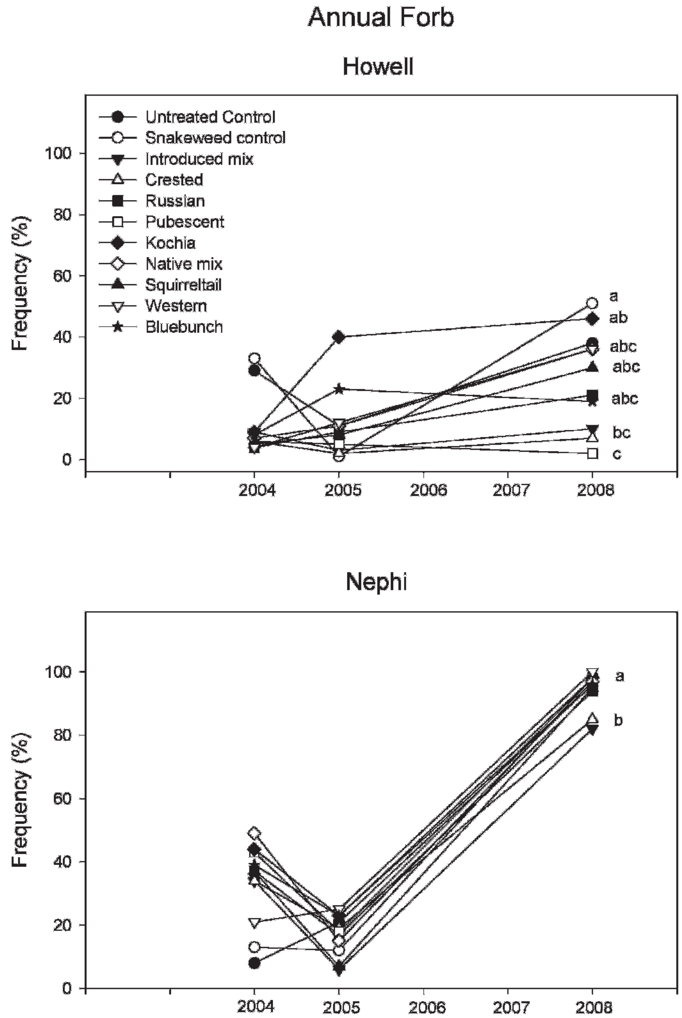

Figure 4. Frequency of annual forbs in treatments plots at Howell and Nephi. Means in 2008 at the end of the study followed by different letters differ ($P < 0.05$).

Discussion

This study was conducted within the framework of the successional weed management model (Sheley et al. 1996; Sheley and Krueger-Mangold 2003). Herbicides were used as the designed disturbance to control snakeweed and associated vegetation and to create a bare-ground, no-till seed bed for seeding desirable species. Seeding of desirable species that are adapted to the site was the controlled colonization. Although it took three attempts during the drought to establish a stand, we were able to compare establishment of the species. We were then able to compare

Table 3. Snakeweed density at the beginning of the study (2001) and from reinvasion after grass establishment.

Year	C[a]	SC	I. mix	CW	RW	PW	K	N. mix	ST	WW	BB
	Plants/m^2										
Howell											
2001	2.95	4.84	7.41	2.85	3.14	5.11	5.35	8.52	4.93	4.15	4.98
2004	0.38	0.02	0.07	0.08	0.14	0.03	0.17	0.11	0.14	0.16	0.08
2006	0.11	0	0.01	0	0	0.01	0.2	0.08	0.08	0.09	0.07
2007	0.05	0.01	0.08	0.01	0.08	0.01	0.40	0.18	0.23	0.08	0.08
2008	0.02 b	0.01 b	0.01 b	0.03 b	0.08 b	0.005 b	0.19 a	0.02 b	0.08 b	0.04 b	0.04 b
Nephi											
2001	5.70	6.68	5.46	3.93	5.17	4.07	5.16	3.97	4.33	4.58	5.15
2004	0.28	0.08	0.02	0.04	0.06	0.10	0.14	0.14	0.04	0.08	0.08
2005	0.18	0.06	0.11	0.17	0.43	0.17	0.36	0.35	0.08	0.18	0.04
2006	0.38	0.15	0.13	0.21	0.32	0.17	0.51	0.26	0.11	0.20	0.13
2007	0.33	0.22	0.15	0.20	0.30	0.21	0.45	0.24	0.10	0.20	0.14
2008	0.32 b	0.20 b	0.18 b	0.22 b	0.38 ab	0.24 b	0.58 a	0.23 b	0.10 b	0.27 b	0.12 b

[a] Abbreviations (see Table 1); C, Untreated control; SC, Snakeweed control; I. mix, Introduced species mix; CW, Crested wheatgrass; RW, Russian wildrye; PW, Pubescent wheatgrass; K, Kochia; N. mix, Native species mix; SC, Snakeweed control; ST, Squirreltail; WW, Western wheatgrass; BB, Bluebunch wheatgrass.

* Means within locations for 2008 followed by different letters differ ($P < 0.05$).

the performance of the seeded species to suppress reestablishment and growth of snakeweed, downy brome, and annual forbs. Crested and pubescent wheatgrass and the introduced grass mix had the best establishment and highest biomass production at Howell, and squirreltail, crested wheatgrass, and both the introduced and native grass mix established best and had the highest biomass production at Nephi. These species also had the greatest suppression of downy brome. Single plant species or mixtures that can rapidly establish and then utilize the available soil moisture and nutrients have the greatest potential to suppress reinvasion of weeds (Svejcar 2003). Specifically, McDaniel et al. (2000) suggested that the management treatment that provides the greatest grass yield and the least amount of bare ground is more likely to minimize the ability of snakeweed to invade a site.

Frequency of annual forbs at Nephi, and downy brome at both Nephi and Howell, increased over the 5 yr of our study in spite of good establishment and persistence of some of the seeded introduced and native grasses. However, their biomass production was suppressed in the seeding treatments that established well. Waldron et al. (2005) reported that crested and Siberian wheatgrass [*Agropyron fragile* (Roth) P. Candargy] established rapidly, and suppressed weed cover (downy brome and annual forbs) throughout their 3-yr study. Native grasses were slow to establish, and subsequently had high weed cover the first year. However, the native grasses (principally western wheatgrass) increased

Table 4. Correlation of frequency of seeded species establishment (2004, 2005) and persistence (2008) with suppression of downy brome and annual forb (frequency and biomass) and snakeweed (density).

		Frequency		Density	Biomass	
Location	Year	Downy brome	Annual forbs	Snakeweed	Downy brome	Annual forbs
		r				
Howell	2004	−0.71	−0.71	−0.49	-	-
	2005	−0.93	−0.15	−0.23	−0.73	0.20
	2008	−0.14	−0.65	−0.10	−0.54	-
Nephi	2004	−0.75	0.53	−0.64	-	-
	2005	−0.85	−0.36	−0.30	−0.91	−0.74
	2008	−0.32	−0.45	−0.40	−0.30	−0.77

Table 5. Relationship between frequency and biomass of seeded species, and their suppression of downy brome and snakeweed at the end of the study in 2008.

Location	Seeded spp.	Seeded species		Downy brome		Snakeweed
		Frequency	Biomass	Frequency	Biomass	Density
		%	kg/ha	%	kg/ha	plants/m^2
Howell	I. mix[a]	98 a	3251 a	72 cd	10 d	0.01 b
	Crested	89 a	2223 b	60 d	38 cd	0.03 b
	Russian	64 bc	1221 d	96 ab	76 bcd	0.08 b
	Pubescent	93 a	2013 bc	87 abc	78 bcd	0.005 b
	Kochia	45 c	162 e	100 a	270 a	0.19 a
	N. mix	91 a	1327 cd	99 a	84 bcd	0.02 b
	Squirrel	82 ab	1006 d	96 ab	91 bcd	0.08 b
	Western	97 a	1173 d	98 ab	63 bcd	0.04 b
	Bluebunch	75 ab	1323 cd	92 ab	122 b	0.04 b
Nephi	I. mix	65 ab	1399 a	96 b	84 cd	0.18 b
	Crested	60 ab	1067 ab	99 a	42 d	0.22 b
	Russian	7 e	77 d	100 a	200 ab	0.38 ab
	Pubescent	35 cd	671 bc	100 a	112 cd	0.24 b
	Kochia	20 de	337 cd	100 a	128 bc	0.58 a
	N. mix	57 ab	879 b	100 a	97 cd	0.23 b
	Squirrel	73 a	821 b	100 a	78 cd	0.10 b
	Western	47 bc	350 cd	100 a	145 bc	0.27 b
	Bluebunch	10 e	115 d	100 a	252 a	0.12 b

[a] Abbreviations (see Table 1); I. mix, Introduced species mix; Crested, Crested wheatgrass; Russian, Russian wildrye; Pubescent, Pubescent wheatgrass; N. mix, Native species mix; Squirrel, Squirreltail; Western, Western wheatgrass; Bluebunch, Bluebunch wheatgrass.

* Means within locations and columns followed by different letters differ ($P < 0.05$).

over their 3-yr study, thereby decreasing weed cover. Prompt reseeding after disturbance is necessary to prevent rapid establishment of downy brome (Evans and Young 1978) and subsequent interference on emerging perennial grass seedlings (Humphrey and Schupp 2004).

Kochia has shown promise for seeding arid and semiarid rangelands and suppressing downy brome (Newhall et al. 2004). It can be slow to establish, but has been found to increase over a 10-yr period and suppress downy brome (Monaco et al. 2003). In our study, kochia did not establish well and we saw no increase over our 5-yr study. In greenhouse pot studies, the single tap root of kochia did not interfere with snakeweed seedlings to the same extent as grass seedlings (Thacker et al. 2009).

Snakeweed did not reestablish in plots where seeded grasses established well or in plots dominated by downy brome. In the previous green house interference trial (Thacker et al. 2009), crested and pubescent wheatgrass seedlings caused significant mortality of snakeweed seedlings and all grass treatments suppressed snakeweed seedling growth. In a subsequent field seeding trial, snakeweed seedlings were transplanted between rows of seeded grasses and within the downy brome–dominated control plots. Snakeweed seedlings experienced high mortality and little growth where other vegetation was established, while snakeweed seedlings planted in bare ground plots flourished (Thacker et al. 2009). Results from the greenhouse and transplanting of snakeweed seedlings within grass seedings in the previous study (Thacker et al. 2009), and the low reinvasion of snakeweed plants in our current study, suggests that snakeweed seedlings are sensitive to competition from all established vegetation, including downy brome, and are not likely to establish within existing vegetation without disturbance.

The importance of disturbance in snakeweed establishment was demonstrated in other snakeweed studies near both of our locations in 2005. Snakeweed readily established on pastures heavily grazed by cattle in spring (Ralphs and Banks 2009), and on plots where grasses were clipped to simulate grazing (Ralphs 2009). Above average spring precipitation facilitated snakeweed germination, and defoliation by grazing or clipping reduced the use of soil moisture by the grasses, thus enabling snakeweed to establish in these two disturbance trials. Snakeweed seedling establishment was significantly less in ungrazed pastures and unclipped control plots of the disturbance trials.

There was a fairly strong negative correlation between establishment of seeded species in 2004 and 2005, and suppression of downy brome and annual forbs (Table 4). Seeded species that established well suppressed downy brome and annual forbs. Those species that did not establish well left microsites open for downy brome and annual forbs to reestablish, which subsequently dominated the plots. However, after 5 yr, frequency of downy brome and annual forbs increased on all plots, thus reducing the strength of the correlations in 2008 (Table 4). The quantitative relationship between the persistence and biomass production of seeded species 5 yr following seeding, and their suppression of downy brome and snakeweed, is illustrated in Table 5. Crested wheatgrass and squirreltail were the most consistent seeded species to establish and persist at both field sites. Although frequency of these species declined over time at Nephi, they maintained a high level of aboveground biomass production. Downy brome reinvaded all of the plots, showing a nearly 100% frequency of occurrence. However, its biomass production was suppressed by the seeded grasses with best establishment and greatest biomass production.

All seeded grasses, and downy brome in the control plots, suppressed reestablishment of snakeweed. Snakeweed established was greatest in the kochia plots where kochia failed to establish the first year. Snakeweed seedlings are sensitive to competition from existing vegetation and will likely establish only following disturbance when soil moisture and nutrients are available.

Sources of Materials

[1] Wheatland Seed, Brigham City, UT.
[2] USDA/ARS Forage and Range Research Lab, Logan, UT.
[3] John Deere Model 71 Flexi Planter.
[4] Brillion Drop Seeder.

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